

ADVANCED TECHNOLOGY FOR ISOLATING PAYLOADS IN MICROGRAVITY

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INTRODUCTION

One presumption of scientific microgravity research is that while in space disturbances are minimized and experiments can be conducted in the absence of gravity. The problem with this assumption is that numerous disturbances actually occur in the space environment. Scientists must consider all disturbances when planning microgravity experiments. Although small disturbances, such as a human sneeze, do not cause most researchers on earth much concern, in space, these minuscule disturbances can be detrimental to the success or failure of an experiment. Therefore, a need exists to isolate experiments and provide a quiescent microgravity environment.

The objective of microgravity isolation is to quantify all possible disturbances or vibrations and then attenuate the transmission of the disturbance to the experiment. Some well-defined vibration sources are: experiment operations, pumps, fans, antenna movements, ventilation systems and robotic manipulators. In some cases, it is possible to isolate the source using simple vibration dampers, shock absorbers and other isolation devices. The problem with simple isolation systems is that not all vibration frequencies are attenuated, especially frequencies less than 0.1 Hz. Therefore, some disturbances are actually emitted into the environment. Sometimes vibration sources are not well defined, or cannot be controlled. These include thermal "creak," random acoustic vibrations, aerodynamic drag, crew activities, and other similar disturbances. On some "microgravity missions," such as the United States Microgravity Laboratory (USML) and the International Microgravity Laboratory (IML) missions, the goal was to create extended quiescent times and limit crew activity during these times. This might be possible for short periods, but for extended durations it is impossible due to the nature of the space environment. On the International Space Station (ISS), vehicle attitude readjustments are required to keep the vehicle in a minimum torque orientation and other experimental activities will occur continually, both inside and outside the station. Since all vibration sources cannot be controlled, the task of attenuating the disturbances is the only realistic alternative.

Several groups have independently developed technology to isolate payloads from the space environment. Since 1970, Honeywell's Satellite Systems Division has designed several payload isolation systems and vibration attenuators. From 1987 to 1992, NASA's Lewis Research Center (LeRC) performed research on isolation technology and developed a 6 degree-of-freedom (DOF) isolator and tested the system during 70 low gravity aircraft flight trajectories. Beginning in early 1995, NASA's Marshall Space Flight Center (MSFC) and McDonnell Douglas Aerospace (MDA) jointly developed the STABLE (Suppression of Transient Accelerations By Levitation Evaluation) isolation system. This 5 month accelerated effort produced the first flight of an active microgravity vibration isolation system on STS-73/USML-02 in late October 1995. The Canadian Space Agency developed the Microgravity Vibration Isolation Mount (MIM) for isolating microgravity payloads and this system began operating on the Russian Mir Space Station in May 1996. The Boeing Defense & Space Group, Missiles & Space Division developed the Active Rack Isolation System (ARIS) for isolating payloads in a standard payload rack. ARIS was tested in September 1996 during the STS-79 mission to Mir.

Although these isolation systems differ in their technological approach, the objective is to isolate payloads from disturbances. The following sections describe the technologies behind these systems and the different types of hardware used to perform isolation. The purpose of these descriptions is not to detail the inner workings of the hardware but to give the reader an idea of the technology and uses of the hardware components. Also included in the component descriptions is a paragraph detailing some of the advances in isolation technology for that particular component. The final section presents some concluding thoughts and a summary of anticipated advances in research and development for isolating microgravity experiments.

STABLE SYSTEM DESCRIPTION

The STABLE system was an experiment with a two-fold purpose: provide an isolated platform for scientific payloads and demonstrate the technology to produce isolation in a microgravity environment. STABLE isolates only the vibration-sensitive portion of a scientific payload from external disturbances. For this flight, the isolated payload was a microgravity-sensitive fluid diffraction experiment named "CHUCK." CHUCK used a combination of lasers, optics and two fluid cells, a control cell and a test cell, to produce a diffraction pattern that was recorded on video. The diffraction pattern changed when the fluid in the test cell was heated. This pattern was very sensitive to microgravity accelerations and required isolation. To isolate the experiment, several types of components are utilized: actuators, umbilicals, sensors, control system, electronics, command input devices and a data acquisition system. To develop a 6-DOF isolation system, the sensors and actuators need to be oriented in an appropriate configuration. Figure 1 represents the configuration of the STABLE system components.

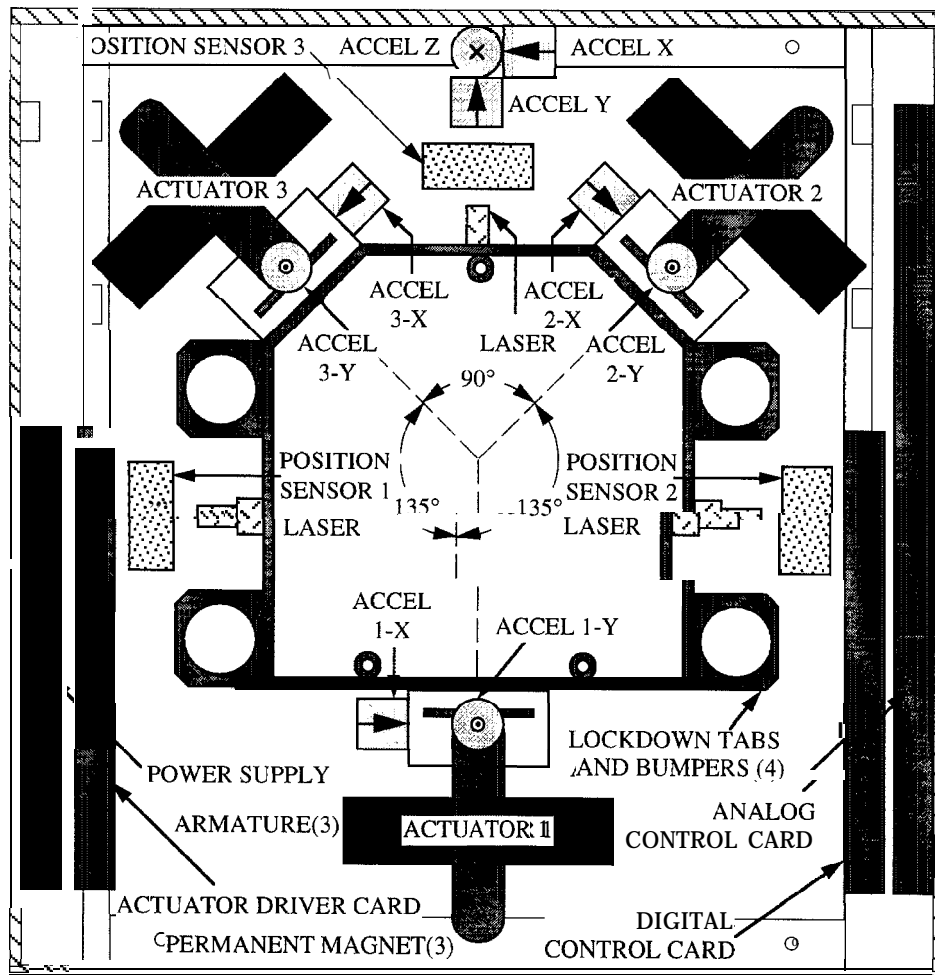


Figure 1. -STABLE System Layout Top View)

The STABLE design utilized three MDA-patented dual-axis electro-magnetic actuators. As shown in Figure 2, the actuators resemble a horseshoe-shaped permanent magnet around a paddle-shaped armature. The magnets provide a constant field which reacts to the varying magnetic field from the armature windings. For simplicity, the permanent magnets were mounted on the floated platform and the armature was mounted to the rigid base. In this mounting configuration, the control currents are not transmitted through the umbilicals. Each actuator provides two axes of force over the full range of free travel, $\pm 1\text{cm}$. This allows the platform to “sway” in the rattlespace to achieve its microgravity performance. The forces required by the actuators, as the platform moves in the rattlespace, are directly dependent upon the umbilical design.

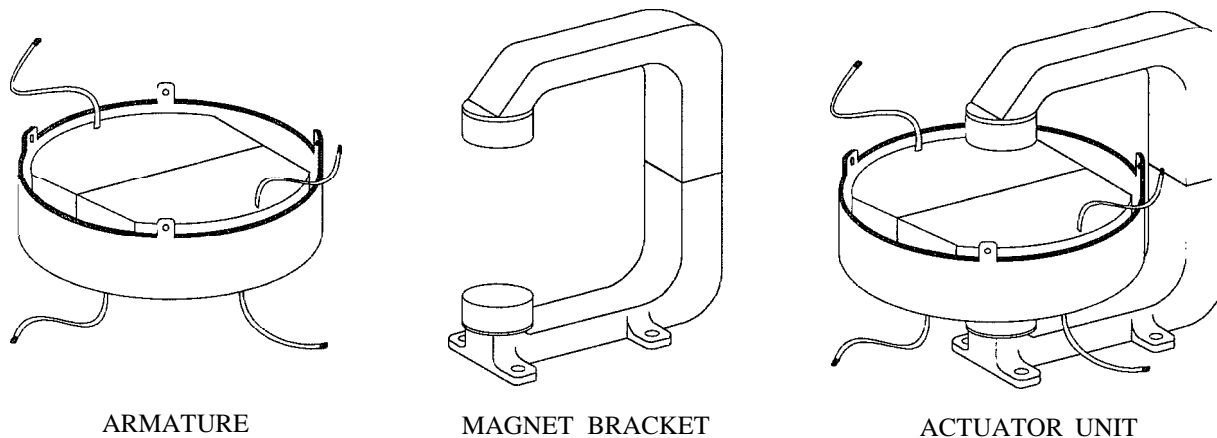


Figure 2. - MDA Dual-Axis Actuator

The STABLE umbilicals are extremely flexible cables which transmit power and signals between the base and the floated platform. Since the actuators do not rigidly connect to the platform, the only means by which the platform can be disturbed is through the umbilicals. For this reason, the umbilicals need to be as flexible as possible. Ideally, the umbilicals should have zero stiffness, but this situation is not realistic with payloads requiring significant power, data, coolant, inert gas or vacuum needs.

For measuring position and acceleration, STABLE incorporated the SC-50D position sensor, from UDT Sensors, and the Sunstrand QA-2000, which is considered the microgravity industry standard accelerometer. These sensors were chosen for several reasons: compact size, durability, performance and relatively low cost. Of the nine single-axis accelerometers used, six were collocated with the actuators for measuring inertial platform accelerations and three accelerometers were mounted to the base to measure the nominal vibration environment for evaluating isolation performance. Three pen lasers, located on the floated platform, produced the reference light spots for the corresponding dual-axis position sensors. This sensor configuration allowed STABLE to measure the relative position of the platform with respect to the base and maintain the platform in a centered position. Refer to Figure 1 for locations and orientations of the STABLE sensors.

The STABLE control system is a combination of a low frequency position controller with a high frequency analog acceleration controller with each axis having its own independent position and acceleration loops. This combination provides continuous high bandwidth, 35 Hz, acceleration control with a low bandwidth, 0.05 Hz, position control system, allowing the platform to drift relatively freely in its rattlespace. Collocating the platform accelerometers with the corresponding actuator's axis provides direct absolute feedback for the acceleration control loop. Since the position sensors are not aligned with the actuator axes, the position controller performed the appropriate transformations to determine the position errors at each actuator gap. Using this gap position information, the position controller gradually recentered the floating platform over a period of minutes while the analog control system operated continuously. The position control system normally operates in a low-gain mode. If the floated platform approached the boundaries of its sway space, the position controller would enter a high-gain mode by increasing the digital control system gains which decreases the effective acceleration control gain. This is necessary to prevent mechanical contact between the platform and base and thus maintain a quiescent microgravity environment for the sensitive payload. Figure 3 is a representation of the STABLE control system architecture.

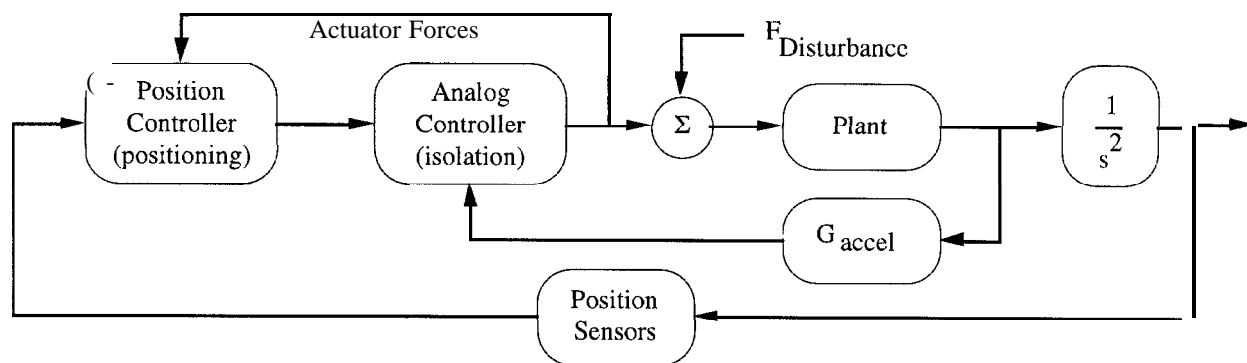


Figure 3.- STABLE Control System Architecture

The electronics that controlled the STABLE system was split into four cards: digital control, analog control, actuator driver and power supply. The core processor for the STABLE digital position controller was an INTEL 80C196KC16-bit microcontroller operating at 8MHz. The microcontroller's analog-to-digital converter (ADC) was operated in the 10-bit mode. The inputs to the ADC were the position sensor outputs, current feedback signals, and the accelerometer temperature measurements. The outputs from the position controller were sent to 12-bit digital-to-analog converters (DAC) on the analog control card and summed with the accelerometer feedback. This signal was passed through a 12-bit multiplying DAC. The multiplying DAC allowed the position controller to take command of the overall system in high-gain mode and provided the flexibility to change the sign of the feedback signal. The combined signal was then sent to the analog control electronics which incorporated a low-pass filter stage with a nominal bandwidth of 50Hz. This results in an acceleration or current command signal. The actuator driver card amplified the current signals using a linear power op-amp stage which provided the actuator drive current.

A data acquisition system (DAS) recorded the STABLE system parameters generated by the control electronics and several temperatures from the CHUCK experiment. The CHUCK video signals were recorded on an 8mm camcorder external to the STABLE system. The parameters measured were: six platform accelerations, three base accelerations, six current commands, twelve position signals, four CHUCK experiment temperatures, and six mode bits. These parameters were recorded by two PC-cards inserted into a Payload General Support Computer (PGSC-486), which is a flight upgraded version of an IBM 750C Thinkpad computer. The PC-cards were 16 channel

12-bit ADC cards with 8 bits of digital I/O from ComputerBoards Inc.. In addition to the previous parameters, nine accelerometer temperatures and a program overflow byte were sent via RS232 to the PGSC-486. The data acquisition system sampled and recorded the accelerometer and current parameters at 250Hz and all others at 10Hz. The DAS system stored the data on the PGSC-486 500-Mbyte removable harddisks. Eight of these harddisks were used in flight and about 72 hours or 3.5-Gbytes of data was recorded during the mission.

The STABLE system was designed for minimal crew interface and attention. The main tasks of the crew were to setup the PGSC-486, enter the current Mission Elapsed Time (MET) and activate STABLE. STABLE utilized six manual switches located on the front panel with corresponding illuminating indicators. These switches were for main power, position mode, acceleration mode, fan power, CHUCK power, and CHUCK heater power. When position mode switch was activated, STABLE would operate only in high-gain mode. When both the position switch and acceleration mode switches were activated together, the STABLE system would operate in the nominal low-gain mode. Other activities performed by the astronaut crew were: change out full PGSC-486 harddisks with a replacement harddisk and operate the CHUCK experiment. CHUCK was operated only four times during the mission, for a total of 8 hours, and its diffraction images recorded on videotape for post-mission evaluation.

The STABLE system achieved its objectives by isolating the CHUCK microgravity-sensitive payload from the “noisy” USML-2 environment and served as a microgravity isolation technology demonstration. Several preliminary analyses of the STABLE data have been performed by MSFC, LeRC, and MDA, and more detailed analyses are under way. Generally, the time history data shows a 25 times reduction in the level of disturbances reaching the isolated platform from the external environment. This isolation factor is consistent throughout the frequencies measured: 0.02Hz - 125 Hz. Another performance measurement is the power required by the STABLE system to perform the isolation. The nominal power required by the actuators during a thruster event in which STABLE maintained isolation was about 3 Watts. This power is in addition to the overhead electronic component usage of about 25 Watts.

CURRENT ISOLATION TECHNOLOGY AND FUTURE ADVANCES

This section describes the current technology behind the other systems mentioned in the introduction and gives the reader an idea of the future direction and recent advances in isolation technology. Since some of these systems, MIM and ARIS, have not disclosed data received from their flight experiments, no performance estimate of these systems is included. For an in-depth analysis of any mentioned technologies and isolation systems, the reader is forwarded to the references on these systems from the original developer.

Generally, it can be stated that the current direction of isolation technology development is to miniaturize the hardware components while maintaining the accuracy, stability and performance of the overall system. The isolation technology hardware descriptions will be separated into the following sections: actuators, sensors, control electronics, and umbilicals. Vibration isolation technology is currently being developed at a rapid pace and engineers are continually developing new methods to isolate systems from noisy environments. Since new technology advancements from other developers are not currently known, only those advances that pertain to future STABLE type systems are included.

ACTUATORS

While the STABLE system used wide gap MDA electro-magnetic actuators, other isolation systems use many different types of actuators, including mechanical, electro-magnetic, and electro-mechanical. The MIM and the LeRC systems use a Lorentz force electro-magnetic type actuator. In their actuators, the area of the magnet is large compared to the coil area, which is different from the MDA actuator, where the magnet area is small compared to the coil area. The ARIS system uses a small-angle motor which drives thin pushrods attached to isolated payload. In this configuration, the ARIS system has a direct mechanical linkage to the payload. Honeywell has used various types of actuators in their systems. Their FEAMIS system utilized electro-magnetic actuators in which an electro-magnet attracts a metallic plate. To isolate the Hubble Space Telescope Reaction Wheel Assemblies, Honeywell used a hydraulic isolator similar to a shock absorber. Some isolation systems, such as 6-DOF STEWART platforms, use traditional hydraulic actuators, linear motors or electric motors attached to screw type mechanisms.

Except for the wide gap, which is necessary to accommodate the required rattle space, the design of an electro-magnetic actuator is similar to an electric motor, and it is theorized that electric motor technology could be adapted to microgravity actuator design. Exotic magnetic materials, such as samarium-cobalt and neodymium, could be used to develop stronger permanent magnetic fields. Advanced methods to contain the stray magnetic field can be implemented to develop more compact and powerful actuators. The goal in future actuator designs is to make the actuator size small, have minimal amount of rattle space for the projected environment and utilize very little power to provide the required forces. An actuator design that meets these objectives requires a study of the following: magnetic materials and flux design, wire size, number of windings, coil orientation and collocation of sensors.

SENSORS

Isolation systems use many different types of sensors for determining the position of the floated platform with respect to the base. Some of sensor types used are: **photovoltaic, photodiode**, hall-effect, capacitive, linear transducers, optical encoders, resolvers and CCD cameras. Both the STABLE and MIM systems used the dual-axis **photodetector** and laser combination while the ARIS actuators have an internal single-axis optical position sensor with a light-emitting-diode (LED) for the source. The LeRC system used a permanent magnet with hall-effect sensor combination and the Honeywell FEAMIS system used a hall-effect sensor for controlling the actuator's magnetic gap. STEWART platform motors and hydraulic actuators could utilize any conventional type of position sensing device, resolver, encoder, or other linear transducers.

Collocation of sensors and actuators is the current trend in the design of STABLE type isolation systems. The position sensors need to be non-contacting and be able to measure the full system **rattlespace** range. Also, the position sensors need to be insensitive to magnetic fields if located near an **electro-magnetic** actuator. Unfortunately, **photodetectors** are sensitive to magnetic fields and need to be magnetically shielded or located away from **electro-magnetic** actuators. A new position sensor concept in development is utilizing the inductance change of the actuator armature coil relative to the magnet position. This unique idea inherently collocates the actuator and position sensor and would not require many external electronic components.

Measuring accelerations in the micro-g range, $1 \times 10^{-6}g$ or μg , is not simple. The Sunstrand QA-2000 accelerometer was used by STABLE, LeRC, MIM and also by the Space Acceleration Measurement System (SAMS). The QA-2000 series uses an **electro-magnetic** coil for force rebalancing and outputs a current signal proportional to the measured acceleration. Unfortunately, some problems exist with this accelerometer: liftoff forces can change the bias, the coil is sensitive to magnetic fields, and the sensitivity to temperature changes is significant at low acceleration levels. Sunstrand has addressed the temperature sensitivity problems in their new QA-3000 series which was used by the ARIS system. Also, depending upon the expected **microgravity** environment, the sensor might have a dynamic range of 0.1 μg to 10,000 pg. This dynamic range is significant for the sensor, amplification stages, and control system. Finally, the noise floor of an acceleration measurement system must be considered. Accelerometer noise can be attributed to **aliasing** and **quantization** effects from digital sampling and the manufacturer's accelerometer noise specifications.

Again, collocation of the accelerometer with the corresponding actuator's axis is important. This reduces the effects of rotational accelerations from corrupting the actual acceleration measurement. Current developments in accelerometer technology include the use of micro-machining to develop sensors that can be placed on an integrated circuit along with the compensation electronics. This advancement will yield sensors that are lighter, more sensitive, and use less power than current technology. Several companies, Endevco, Clifton Precision and EG&G [C Sensors, are working on these types of accelerometer designs for automobile **airbags**, and it is theorized that these sensors could accommodate **microgravity** acceleration ranges by changing the internal coefficients.

CONTROL ELECTRONICS

The control systems and electronics for isolating payloads are as varied as the scientific payloads themselves. STABLE is unique in that it utilizes a combination of both analog and digital control. The MIM and ARIS systems use only digital control for both the acceleration and position control laws and both use high performance digital signal processors (DSP's) for performing the control law calculations. The ARIS system employed the 3 Dimensional Microgravity Accelerometer (3-DMA) system to perform overhead functions and communicated with 3-DMA using both RS232 and MIL-STD-1553B data links. The 3-DMA overhead functions are: recording acceleration measurements, interfacing to the PGSC-486, change control gains, reprogramming, postprocessing, command, control, and data **uplink** and **downlink**. To perform its overhead **functions**, the MIM system incorporated a 486 type single-board computer into its electronics package. These high performance processors, DSP's and 486 computers, compute the control law equations, transformation matrices, sample sensors, and perform overhead functions at a very fast sampling rate, usually $\sim 1000Hz$. This fast sampling rate is necessary to achieve a reasonable control bandwidth of- 100Hz. Unfortunately, these high performance processors are currently very susceptible to single-event upsets (SEU's), which can cause systems to go to an unknown state. If the SEU's are not accounted for by software or hardware means, they can cause an isolation system to "crash" into the containment bumpers, thus violating the isolation requirements. To overcome this problem, the ARIS and MIM systems have software and hardware watchdog timers that reset the system in case a SEU was detected.

One of the advances in digital control will actually come from the collocation of position sensors and actuators. Collocation will eliminate the need to transform the position information into actuator gap coordinates, allowing multiple 2-DOF systems to operate together to achieve isolation. Reducing the calculation time, by collocation, will not reduce the trend to use DSP's and 32 or 64-bit processors. Since these high performance processors are designed for these applications, the research direction will be to find means to either **shield** or radiation-harden the

core processor from the space environment. Once these processors become space qualified, the use of both analog and digital control together will decrease. If the position control bandwidth in isolation systems continues to remain relatively low, ≤ 1 Hz, the use of slower, more accurate, >16 -bit, ADCs will become prevalent, allowing precision positioning of the isolated payload. Another advance in data transmission for isolation systems will be the use of either infrared (IR), radio-frequency (RF) or optic fiber technologies. New advances in cellular phone technology and the new Infrared Data Association (IRDA) standard 1.1 will allow for transmission of data between the payload and base, at rates required for control of payload physical processes. The transmission interface will require a minimal set of overhead electronics, but this transmission method would reduce the number of umbilicals.

UMBILICALS

Flexible umbilicals are critical in the design of isolation systems. The stiffness of the umbilicals is the primary factor in determining the required actuator forces, the transmission of disturbances to the payload and the control system bandwidth. The umbilicals must also have the capacity to transfer resources to and from the payload. These resources can include any combination of: power, data, video, vacuum resource and exhaust, fire detection and maintenance, coolant supply and return and gaseous supply. The STABLE experiment used two flexible umbilicals, one for power and the other for data and video, while the MIM system provided only power and data services to the isolated experiment. The ARIS design included a full complement of umbilicals and was the first isolation system to integrate many different types of umbilicals and materials in the design process.

Recent advances in umbilical technology include: umbilical material studies, coiling, splints, and umbilical followers. A study of new materials and umbilical designs is being performed for the Space Station Furnace Facility project by the MSFC Propulsion Laboratory. A Dupont/Dow F200 barrier hose material is one of the materials being tested for vacuum, fluid and inert gas umbilicals. The materials and manufacturing processes for all flight umbilicals are defined by the Space Station Qualified (SSQ) specification. Even though these materials have a low stiffness property, it is also helpful to coil the umbilicals to further reduce the stiffness. Figure 4 shows a set of coiled umbilicals for the ARIS system. If two umbilicals touch, the disturbance transmission path is "shorted," which increases the effective stiffness. To prevent this from occurring, small splints can be inserted to keep adjacent coils from touching. The splints can be semi-flexible to help isolate adjacent umbilicals, but rigid enough to keep the coils at a predetermined distance. Although these methods reduce umbilical stiffness, large bias forces can develop from the movement of the isolated payload. To overcome this problem, an umbilical follower can be implemented to reduce these bias forces. An umbilical follower is a 3-DOF mechanism that moves the base of the umbilical set to minimize the average actuators' currents, which corresponds to the umbilical bias forces.

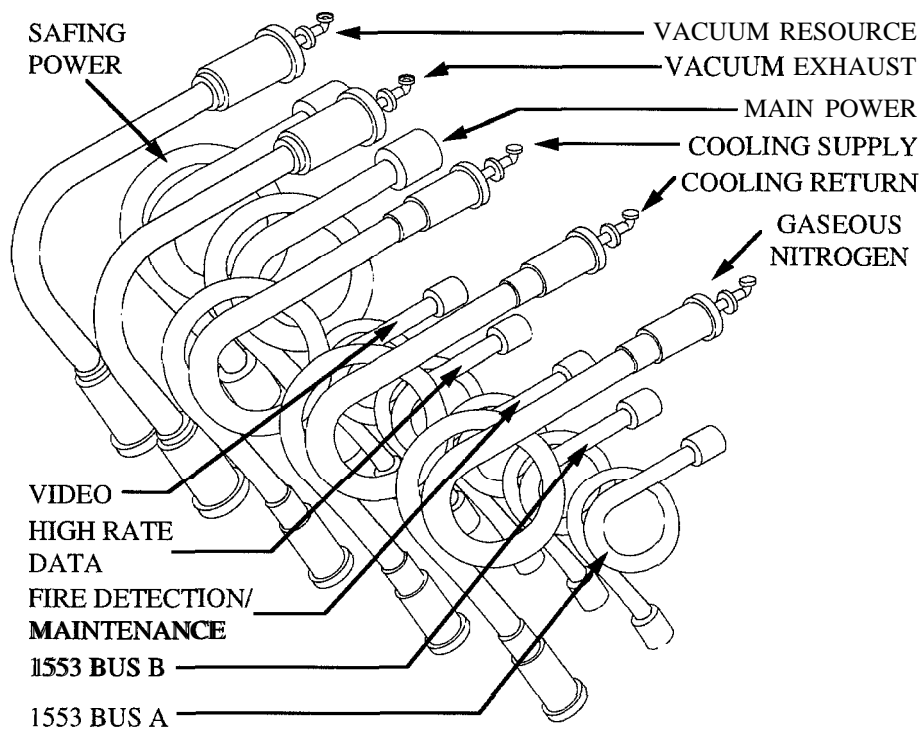


Figure 4.- ARIS System Umbilicals

CONCLUSIONS AND FUTURE DIRECTIONS

The microgravity isolation field has a long history beginning in the early 1970's with the Honeywell corporation. Twenty-five years later, isolation technology has improved significantly and the need for microgravity isolation is now more important considering the many different types of disturbance sources, known and unknown, present on the ISS. The STABLE system was the first flight of an experiment to demonstrate microgravity isolation and was soon followed by the MIM and ARIS systems. Although MIM and ARIS have not disclosed their isolation performances, the STABLE system proved that experiments can be isolated from space environment disturbances, including crew activity, while using minimal resources. All the isolation systems mentioned have assisted in defining the core technology for microgravity isolators. The technological basics of implementing microgravity isolation are very straightforward, and anyone skilled in motion control technology can make significant contributions. Any contributions to the core technologies, actuators, sensors, umbilicals, control systems and electronics, may apply to many different industries with similar requirements. Some of these industries include motion control, robotics, vibration suppression, manufacturing and vehicle ride control. Core technological research, like MSFC's umbilical material and design study, is essential for developing the next generation of hardware components for microgravity isolators.

Current technology development and research are directed at every aspect of isolation systems. New types of actuators, sensors, umbilicals, control architectures and electronics are being developed as well as a new isolator design for ISS racks, experimental payloads and the ISS microgravity glovebox. Future actuator designs will be smaller with improved magnetic flux containment and have both position and accelerometer sensors collocated with the actuator. Micro-machined accelerometers specifically designed for microgravity applications will be necessary for smaller isolator designs. Novel position sensor techniques are being developed which integrate the actuator coils as a position sensor. New umbilical materials and umbilical followers are being designed to reduce bias forces. To control isolator systems, future designers will use space qualified microprocessors and DSP's and more accurate, ≥ 16 -bit, ADC's and DAC's. Current control architectures use either digital or a combination of digital and analog control, but future isolators will include some type of adaptive control to account for different payload inertial properties. Finally, new isolator designs might use either IR, RF or even optical fibers for data transmission between the base and the isolated platform. In general, new and improved isolation systems need to be designed which have simple interfaces and use minimal overhead volume and power. In summary, these current areas of study and other technologies yet to be invented will advance isolation systems into the twenty-first century.

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